

RASMOT-3D PRO: a 3D motif search webserver

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Received January 30, 2009; Revised April 8, 2009; Accepted April 16, 2009

ABSTRACT

Detection of structural motif of residues in protein structures allows identification of structural or functional similarity between proteins. In the field of protein engineering, structural motif identification is essential to select protein scaffolds on which a motif of residues can be transferred to design a new protein with a given function. We describe here the RASMOT-3D PRO webserver (<http://biodev.extra.cea.fr/rasmot3d/>) that performs a systematic search in 3D structures of protein for a set of residues exhibiting a particular topology. Comparison is based on C α and C β atoms in two steps: interatomic distances and RMSD. RASMOT-3D PRO takes in input a PDB file containing the 3D coordinates of the searched motif and provides an interactive list of identified protein structures exhibiting residues of similar topology as the motif searched. Each solution can be graphically examined on the website. The topological search can be conducted in structures described in PDB files uploaded by the user or in those deposited in the PDB. This characteristic as well as the possibility to reject scaffolds sterically incompatible with the target, makes RASMOT-3D PRO a unique webtool in the field of protein engineering.

INTRODUCTION

Structural genomics projects have led to the exponential growth of the number of protein structures deposited in the Protein Data Bank (1), creating an urgent need for efficient bioinformatics tools to extract the considerable amount of information contained in this database. A large number of developed methods are based on global 3D structures similarities. These fold comparison methods often do not allow identifying similarities among functionally significant residues such as metal-binding

sites, catalytic sites of enzymes or ‘hot spot’ residues (2) involved in protein–protein interactions. Indeed, proteins with the same fold or even homologous proteins can exhibit a variety of biochemical functions (3). Conversely, proteins with different folds can perform the same function with the same set of residues and a similar mechanism (4). Specific methods should then address this particular problem of identifying functional motif similarity among proteins of different folds. These methods have been used for instance to identify specific enzymatic activity (5), to design proteins ligands (6–8) and new enzymes (9–11).

Several web servers currently give access to 3D motifs based methods for protein structures analysis. MultiBind (12) recognizes 3D-binding patterns common to several protein structures submitted. The KFC server (13) predicts binding hot spots at a particular protein–protein interface. MegaMotifBase (14) provides a compilation of structural motifs identified in protein families that may permit the user to assign a particular protein to one of these families. Other web servers search for known motifs in protein structures. PAR-3D (15) uses 3D motifs to identify several different classes of proteases or metal-binding sites in a submitted protein structure. Superimpose (16) allows searching for a specific 3D motif in protein structure databases. The SPASM server (17) allows identification of 3D motif in a PDB derived database. However, none of these web servers are specifically dedicated to the identification of protein scaffolds to transfer residues for protein ligand design. Such a website would ideally include an extensive search in all structures deposited in the PDB including the many conformers deposited in each file of NMR structure. Another essential characteristic of 3D search methods dedicated to protein ligand design is to take into account the steric aspects of the interaction of the protein scaffold with the considered target. These characteristics could permit to extensively take part of the topological information contained in the PDB and to identify very rapidly good protein scaffold candidates.

Here we describe RASMOT-3D PRO, a webserver that permits to search in protein structures for residues exhibiting similar topology as a user-defined reference 3D motif.

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It can then be useful in the fields of function identification and protein design. It can also be used to identify any type of 3D specific arrangement of residues such as supersecondary structures or small domains. The webserver is freely accessible at <http://biodev.extra.cea.fr/rasmot3d/>.

IMPLEMENTATION

RASMOT-3D searches in protein structures for sets of residues in a topology similar to the motif given in input (hereby called reference motif). Each protein structure file is examined independently. Comparison is based on C α and C β atoms exclusively and can be divided into two sequential steps: inter-atomic distances comparison and root mean square deviation (RMSD). We consider for illustration a reference motif R composed of n residues $\{r_1, r_2, \dots, r_n\}$ and an examined protein P of N residues $\{p_1, p_2, p_3, \dots, p_N\}$.

(i) Inter-atomic distances comparison step is described in the following paragraph and a corresponding scheme is provided in Supplementary Data S1. The initial step consists in calculating the $2n(n-1)$ inter-atomic distances between all C α and C β atoms of the residues composing the reference motif. Then, examined protein residues are combined sequentially, trying to form sets of residues S , composed of n residues $\{s_1, s_2, \dots, s_n\}$, with C α and C β inter-atomic distances similar to those calculated in the reference motif. Starting from two residues $s_1=p_i$ and $s_2=p_j$, considered as equivalent to r_1 and r_2 , distances between C α and C β atoms of these two residues s_1 and s_2 are calculated. If one of these distances differs by more than the threshold (delta-dist) from the corresponding distance calculated in the (r_1, r_2) pair, residue p_j in position s_2 is rejected and a p_{j+1} is tested. Conversely, if all these distances differ by less than delta-dist, residue $s_3=p_k$ is added and distances between C α and C β atoms of s_3 with C α and C β atoms of s_1 and s_2 are calculated and compared to the corresponding distances characterizing (r_1, r_2, r_3) in the reference motif. Residues are added this way to the set. When a set of n residues $\{s_1, s_2, \dots, s_n\}$ satisfies all the inter-atomic distance restraints, the second topological filter RMSD is applied [see (ii)]. Then the following set (with a new residue in position s_n) is tested. This method, which allows pruning of the search tree as early as possible, is applied until all combinations of examined protein residues have been tested.

(ii) Root mean square deviation (RMSD) filter is calculated on sets of residues that satisfy all inter-atomic distance restraints [see (i)]. Each of these set of residues $S \{s_1, s_2, \dots, s_n\}$ are superimposed onto the reference motif $R \{r_1, r_2, \dots, r_n\}$ by root mean square fitting of the C α and C β atoms. Its coordinates are rotated and translated to minimize the RMSD on the C α and C β atoms of S relative to R . After superimposition, the resulting RMSD value is compared to the threshold set in input (RMSD-max). The tested set of residues $S \{s_1, s_2, \dots, s_n\}$ is rejected if the RMSD is larger than this threshold.

(iii) In addition, an optional steric filter was implemented. When searching for a binding or a catalytic site, it can be useful to select only scaffolds allowing residues

topologically equivalent to the reference motif to interact with a specific target T . Indeed, it is not uncommon that scaffolds selected via identification of a motif S , topologically similar to the reference motif R , possesses structural elements that preclude the binding to T due to steric hindrance. To address this specific problem, we implemented a steric score calculated for each protein P exhibiting a set of residues S that satisfies the RMSD criterion. When one has in hand, a structure of the reference protein containing motif R in interaction with the target T , the motif S in the identified protein scaffold P is superimposed on the reference motif R . Then, the inter-atomic distances are calculated between all the atoms of protein P and target T . If the distance between an atom of P and an atom of T is lower than the sum of their radii, the score is increased by a value taking into account the interpenetration distance and the distance of the atom of P to the main chain of this protein. This allows giving less weight to the steric clash involving side-chain atoms than those involving the main chain ones. Finally, if this score is larger than a threshold, the corresponding set of residues S is rejected. This threshold has been set empirically to allow for minor interpenetration. This is justified because protein and target are treated as rigid bodies by the program.

From the above description, it can be seen that the search method implemented in RASMOT-3D PRO shares some similarities with the SPASM program (18) but presents specific features dedicated to the identification of protein scaffolds onto which transfer functional motifs. One central feature of RASMOT-3D PRO is that the type of each residue in the selected motif can be different than the corresponding residue in the reference motif. This is possible without bias because the search is based on the C α and C β atoms. The method treats protein chains in a single PDB file as independent structures. For NMR derived structures, all the models are evaluated. For each identified set of residues, only the model with the lowest RMSD and satisfying the steric criteria is presented in the results.

USING THE RASMOT-3D PRO WEB SERVER

Submitting a query

The RASMOT-3D PRO only requires the reference motif residues coordinates uploaded as a PDB file to be launched. Several other parameters are available but are optional or set to default values. They are divided into four subgroups:

Examined protein files. In this part, the user can determine the PDB files containing the coordinates of the proteins in which to search for the motif. Two options are available. The user can upload its own PDB files (up to 10) or search into one of the four NCBI non-redundant PDB chain sets (<http://www.ncbi.nlm.nih.gov/Structure/VAST/nrpdb.html>) obtained by clustering using four different sequence-similarity cutoffs (P -values of 10^{-7} , 10^{-40} , 10^{-80} and 100% identity).

Selection parameters. These parameters permit to set the threshold values described in the previous section: the maximal deviation for inter-atomic distances (delta-dist) and the maximal RMSD. They are set to default values but can be changed by the user. In addition, two pre-filters are available. (a) Motif search can be restricted to residues identical or with similar physical properties than their equivalent in the reference motif. (b) Examined scaffolds can be restricted to proteins with length size within defined limits.

Steric filter. If needed, the user can upload the coordinates in PDB format of a target positioned relative to the reference motif to eliminate identified scaffolds that make important steric clashes with this target. The steric score threshold is set to a fixed value determined empirically to give acceptable results.

Personal information. Before submitting, the user can optionally provide an e-mail address where a link to the results will be sent when the run is completed.

Choosing parameters

Calculation can take from few seconds for uploaded structures search to several hours for non-redundant PDB search. For the latter case, delta-dist thresholds must be chosen with caution. Large values for these parameters

will increase exponentially the number of sets of residues to fit on the reference motif. Therefore, the computational time will increase dramatically. As the number of solutions reported is limited to the 250 lowest RMSD, there is no advantage to choose large delta-dist value. Thus, we suggest the users of the RASMOT-3D PRO to start their search with default parameters and to increase progressively the threshold if needed.

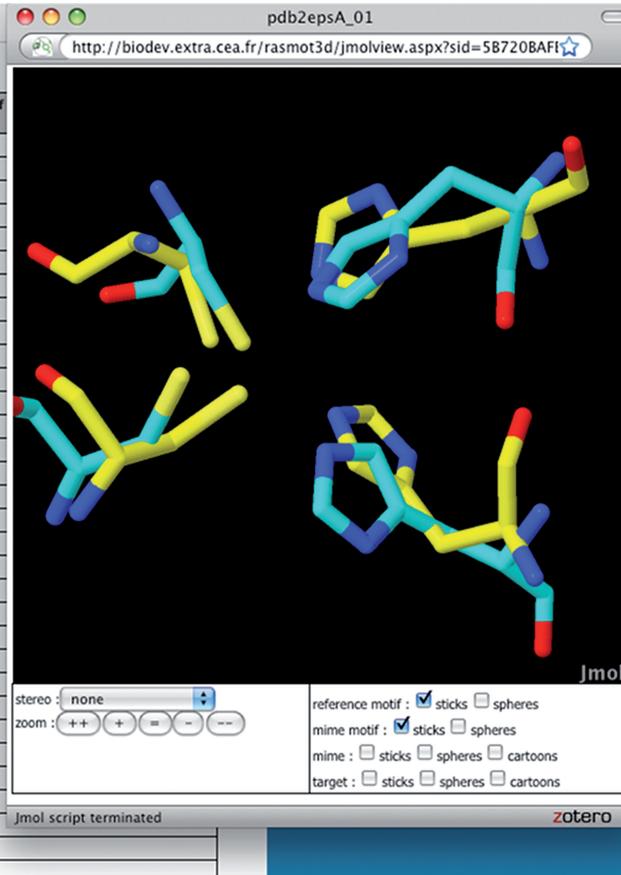
Viewing the results

Figure 1 shows an example of RASMOT-3D PRO results page. Solutions are sorted according to the motif RMSD. Only the 250 firsts scaffolds are displayed. For each solution, the data reported are: the PDB file name of the protein containing the set of residues of similar topology, the chain id, the size of this chain, the best model id for NMR derived structures, the RMSD, and the identity of the residues in the set identified. For known PDB file names, a link to the PDBsum (19) is provided. Finally, the scaffolds identified can be examined with the Jmol interactive online molecular viewer (<http://www.jmol.org>) without any plugin installation. Clicking on the name of the solution in the results table opens a window with the online molecular viewer. Opening it in a separate window allows simultaneous examination of several solutions that can therefore be easily compared. The reference motif given

Results

found 80 solutions (80 detailed)

file (Jmol view)	protein (PDBsum info)	chain	size	model	rmsd	motif
pdb2epa_00	2epa	A	72	20	0.15	CYS 20 , CYS 25 , HIS 38 , HIS 42
pdb2zentA_00	2zent	A	48	7	0.16	CYS 353 , CYS 358 , HIS 371 , HIS 375
pdb2zelnA_00	2eln	A	38	5	0.28	CYS 12 , CYS 17 , HIS 30 , HIS 34
pdb1zw8A_00	1zw8	A	64	13	0.30	CYS 5 , CYS 10 , HIS 23 , HIS 28
pdb1zw8A_01	1zw8	A	64	14	0.33	CYS 42 , CYS 47 , HIS 60 , HIS 65
pdb1klrA_00	1klr	A	30	10	0.33	CYS 5 , CYS 8 , HIS 21 , HIS 26
pdb1zfdA_00	1zfd	A	32	17	0.35	CYS 44 , CYS 49 , HIS 62 , HIS 66
pdb2zelvA_00	2elv	A	36	1	0.37	CYS 12 , CYS 15 , HIS 28 , HIS 32
pdb2ct1A_00	2ct1	A	77	18	0.37	CYS 18 , CYS 21 , HIS 34 , HIS 39
pdb2zelxA_00	2elx	A	35	8	0.42	CYS 10 , CYS 13 , HIS 26 , HIS 31
pdb2eloA_00	2elo	A	37	7	0.43	CYS 12 , CYS 15 , HIS 28 , HIS 33
pdb2zeluA_00	2elu	A	37	9	0.43	CYS 12 , CYS 15 , HIS 28 , HIS 33
pdb2yrmA_00	2yrm	A	43	9	0.44	CYS 13 , CYS 16 , HIS 29 , HIS 34
pdb1znrfA_00	1znrf	A	25	36	0.46	CYS 3 , CYS 6 , HIS 19 , HIS 23
pdb1yu1A_00	1yu1	A	54	1	0.47	CYS 36 , CYS 39 , HIS 52 , HIS 57
pdb2elgA_00	2elg	A	36	8	0.47	CYS 12 , CYS 15 , HIS 28 , HIS 32
pdb2elrA_00	2elr	A	36	13	0.47	CYS 12 , CYS 15 , HIS 28 , HIS 32
pdb2bab3A_00	2ab3	A	29	1	0.48	CYS 5 , CYS 10 , HIS 23 , HIS 27
pdb1njqA_00	1njq	A	37	19	0.48	CYS 8 , CYS 11 , HIS 24 , HIS 28
pdb2elmA_00	2elm	A	37	6	0.49	CYS 12 , CYS 15 , HIS 28 , HIS 33
pdb2zelvA_00	2elv	A	37	12	0.49	CYS 12 , CYS 15 , HIS 28 , HIS 33
pdb2ej4A_00	2ej4	A	95	19	0.50	CYS 16 , CYS 31 , HIS 44 , HIS 49
pdb1wjpA_00	1wjp	A	107	6	0.51	CYS 72 , CYS 75 , HIS 88 , HIS 93
pdb2ct5A_00	2ct5	A	73	9	0.51	CYS 32 , CYS 35 , HIS 51 , HIS 56
pdb1k2fA_00	1k2f	A	190	1	0.53	CYS 128 , CYS 135 , HIS 147 , HIS 152
pdb1srkA_00	1srk	A	35	6	0.53	CYS 10 , CYS 13 , HIS 26 , HIS 30
pdb2elpA_00	2elp	A	37	15	0.54	CYS 12 , CYS 15 , HIS 29 , HIS 33
pdb2ct1A_01	2ct1	A	77	7	0.54	CYS 48 , CYS 51 , HIS 64 , HIS 69
pdb1ej6C_00	1ej6	C	1221	1	0.55	CYS 183 , CYS 186 , HIS 199 , HIS 203
pdb1x6hA_00	1x6h	A	86	7	0.55	CYS 18 , CYS 21 , HIS 34 , HIS 39
pdb2eltA_00	2elt	A	36	10	0.55	CYS 12 , CYS 15 , HIS 28 , HIS 32
pdb2d9hA_00	2d9h	A	78	3	0.58	CYS 10 , CYS 13 , HIS 26 , HIS 30



The screenshot shows the Jmol viewer displaying four protein structures (2epa, 2zent, 2eln, 1zw8) with their respective motifs overlaid. The motifs are shown as sticks and spheres. The Jmol interface includes controls for stereochemistry (none, left, right), zoom (++ + = - --), and representation options (reference motif: sticks, spheres; mime motif: sticks, spheres; mime: sticks, spheres, cartoons; target: sticks, spheres, cartoons). A message at the bottom says "Jmol script terminated".

Figure 1. RASMOT-3D PRO output example: results for Cys-Cys-His-His zinc finger motif search into the non-redundant PDB chain set (P-value of 10^{-7}).

in input, the superimposed set of residues identified in the particular PDB file and the target, if provided, can be visualized. Reference motif is colored in cyan, identified residues and scaffold in yellow and target in grey. The user can choose which molecule or motif to display and select different representation modes.

When the search is conducted on one of the four NCBI non-redundant PDB chain sets, the online results pages are accessible via the URL sent by e-mail during 24 h. An archive can be downloaded from the server. It contains: (i) a file with the parameters used, (ii) a results file with one solution per line and fields separated by tabulations that can be easily imported in a spreadsheet program, and for each solution (iii) a PDB file containing the coordinates of the scaffold and (iv) a PyMol (<http://www.pymol.org>) visualization script file.

CASE STUDIES/DISCUSSION

Ligand design is still a considerable goal in biology with obvious applications in basic sciences, diagnosis and therapeutics, but it remains a challenging task. RASMOT-3D PRO was initially elaborated to identify platforms to transfer a functional motif by systematic examination of the structures deposited in the PDB. In a previous work (7) we used this approach to design a Kv1.2 potassium channel blocker and we obtained several micromolar blockers for this channel. With a similar method, using C α and C β inter-atomic distances, RMSD and steric filtering, Liu and coworkers designed the pleckstrin homology domain PLC δ_1 -PH to bind the human erythropoietin receptor by grafting the key interacting residues of the human erythropoietin (8). These works clearly demonstrated the value of the approach to design protein ligands. However, one conclusion of our previous work (7) was that the success of the method depends on the number of identified scaffolds. Indeed, after topological *in silico* scaffold selection, several steps must be overcome. In particular, the designed molecule must be produced, folded and purified that, in some case, can be a very difficult or even an impossible task. Other very impressive works in the field of computational design of enzymes relying on the selection of scaffolds showed that, despite the sophistication of the model used, only a fraction of the designed enzymes displayed a significant activity (20). Consequently, in computational design methods relying on the identification of scaffolds, it is essential to analyze extensively the PDB to return a diversity of protein scaffolds thereby increasing the chance of success. As an illustration of the capacity of RASMOT-3D PRO to identify protein scaffolds by systematic examination of the PDB, we considered the work of Vita and coworkers that engineered a mini-protein binding the HIV-1 gp120 by transfer of a group of CD4-binding residues onto scyllatoxin (21). At the time of this work, the selection of the scaffold was made without the help of any bioinformatics means, but on a visual basis. Scyllatoxin was selected because it presented a β -hairpin motif similar to the CD4-binding region. We used RASMOT-3D PRO to search for scaffolds possessing a β -hairpin similar to that formed by

Table 1. Sorted solutions of the CD4 β -hairpin motif search in the non-redundant pdb chain set with RASMOT-3D PRO

	Name	Size	Description	RMSD
1	1cdy	178	CD4 mutant G47S	0.52
2	2z59	109	adrm1	0.55
3	1kla	112	tgf-b1 growth factor	0.55
4	1mm0	36	termicin antimicrobial peptide	0.63
5	1v5r	97	gas2 domain of growth arrest protein 2	0.70
6	1ne5	42	Herg specific scorpion toxin cneng1	0.70
7	1sis	35	scorpion insectotoxin i5a	0.70
8	2oox	93	transferase	0.71
9	2hgc	78	unknown function	0.71
10	3ca7	50	EGF domain of Spitz	0.72
11	1ph2	31	<i>PO5-NH2</i>	0.72
12	2k1n	55	abrB	0.73
13	1rpy	85	dimeric sh2-signaling protein	0.74
14	2ea9	103	unknown function	0.75
15	1du9	28	BMP02 scorpion toxin	0.77
16	2dir	98	THUMP domain RNA-binding protein	0.79
17	2jna	104	unknown function	0.79
18	2jtv	65	unknown function	0.81
19	2qhd	122	ecarpholin	0.84
20	1a96	150	Xprtase	0.87
21	2k5l	81	unknown function	0.96
22	2k6z	120	unknown function	0.96
23	1quz	34	scorpion toxin hstx1	1.00

The structure representative of the cluster of the scyllatoxin in the non-redundant pdb chain set is represented in italic.

residues 38–47 in CD4 making no major steric clash with the HIV-1 gp120 once the motifs are superimposed. We used the most non-redundant pdb chain set with *P*-value of 10⁻⁷, delta-dist of 1.5 Å and RMSD of 1.0 Å. CD4–gp120 complex coordinates were taken from PDB file 1g9n. We restricted the search to proteins smaller than CD4 (less than 180 residues). This search returned 23 proteins of different size and scaffold among which several scyllatoxin analogs (Table 1). We also identified scaffolds that better reproduce the R59 critical residue topology, as illustrated in Figure 2, which could be used as well to design mimetic protein of the CD4. A second example of RASMOT-3D PRO use illustrates its ability to identify proteins sharing a similar function relying on the presence of a conserved functional motif but located in very different structural contexts. We considered serine endopeptidases that include proteins with different folds (22), which are all characterized by the serine/histidine/aspartate catalytic triad. We then searched for this three residues motif, using target steric filtering and default parameters (in the most non-redundant protein structures database, with delta-dist and RMSD threshold both set to 0.8 Å). Coordinates of target and motif were extracted from beta-trypsin/BPTI complex described in PDB file 2PTC. We found 47 solutions, all of them being serine proteases from different organisms, with different folds (23). Figure 3 displays one example of two serine proteases identified by RASMOT-3D PRO, possessing the Ser/His/Asp motif supported by completely different architectures. RASMOT-3D PRO is then able to identify proteins sharing similar function on the basis of common 3D functional motif. These two examples show that the webserver

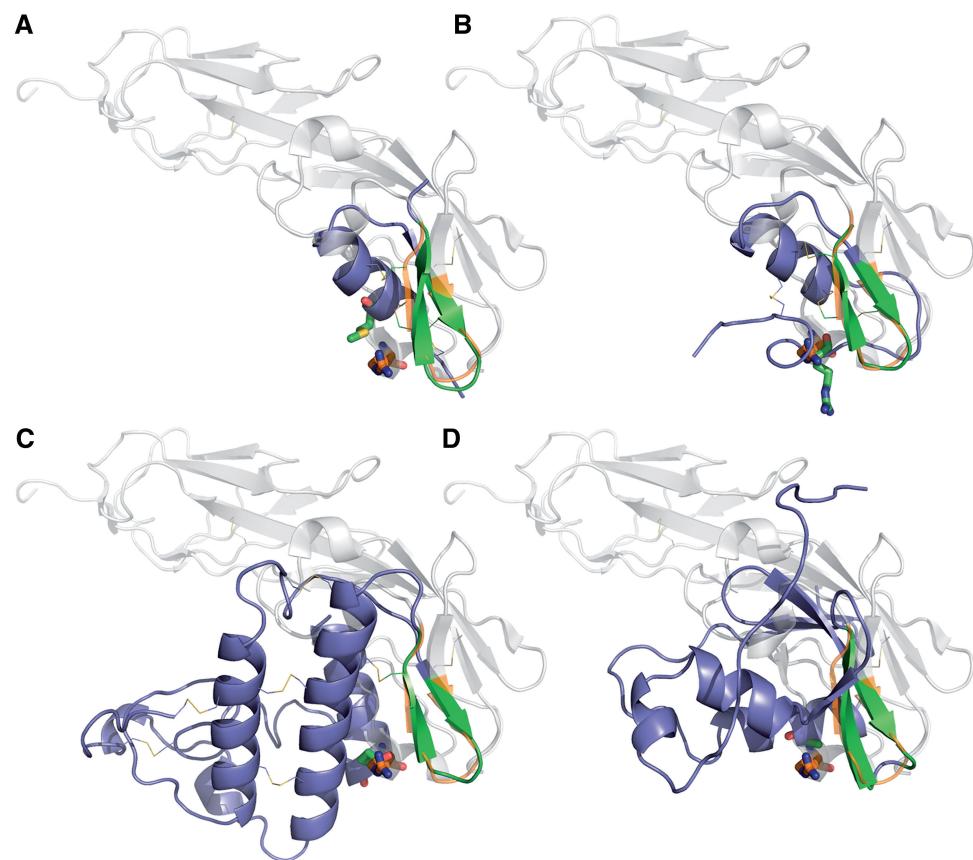


Figure 2. Comparison of the superimposition of the CD4 with the scyllatoxin and three scaffolds identified by RASMOT-3D PRO. CD4 is colored in light grey with beta-hairpin motif and R59 in orange. The mimetic scaffolds are colored in blue with beta-hairpin motif and R59 equivalent residue in green. (A) scyllatoxin (1scy) identified by Vita *et al.* (21), (B) Cnerg1 (1ne5) another scorpion toxin, (C) ecarpholin (2 qhd) and (D) gas domain (1v5r) with an unrelated fold.

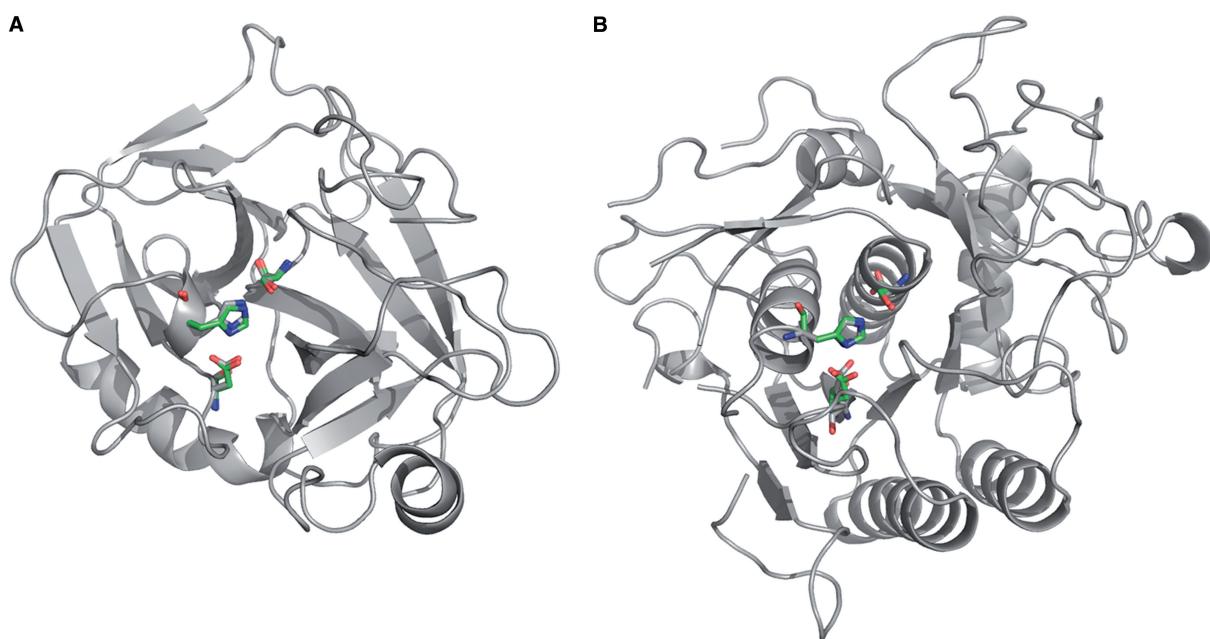


Figure 3. Comparison of two different serine protease folds obtained by searching the Ser-His-Asp catalytic motif with RASMOT-3D PRO: (A) trypsin (1os8) and (B) sphericase. Reference motif is represented in green, identified scaffold in grey.

RASMOT-3D PRO might give a very useful contribution in scaffold-based protein engineering and in protein function assignment.

SUPPLEMENTARY DATA

Supplementary Data are available at NAR Online.

FUNDING

Funding for open access charge: Commissariat à l'Energie Atomique, France.

Conflict of interest statement. None declared.

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